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Design of a Remotely Controlled Hovercraft Vehicle for Spill Reconnaissance

Developmental Sciences, Inc.
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DESIGN OF A REMOTELY CONTROLLED HOVERCRAFT VEHICLE FOR SPILL RECONNAISSANCE

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16. ABSTRACT

This program was undertaken to prepare a conceptual design for a practical prototype of a remotely-controlled reconnaissance vehicle for use in hazardous material spill environment. Data from past hazardous material spills were analyzed to determine the type of vehicle best suited for the reconnaissance duty and the vehicle's performance standards. Based on the environmental conditions present at a "typical spill," the desired vehicle capabilities, and the level of operated skill that could reasonably be expected, the vehicle selected was a ground effect machine or hovercraft. A skirted hovercraft design was chosen over a peripheral-jet design because of power requirements. The 8 ft diameter, 300 lb, skirted prototype should be able to clear obstacles approaching 18 in. in height using only 4 hp versus the 15 hp required by a peripheral-jet craft. The craft, of sandwich panel construction, using Nomex honeycomb between Kevlar face-sheets, would yield a high strength and stiffness-to-weight structure. State-of-the-art batteries and electric DC motors provide a propulsion system which gives the vehicle an estimated 1.5 hr endurance at maximum power output and an effective operating range of 1/2 mi. The design includes television and gas sensors for remote reconnaissance of the spill area.

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Ground-effect machine	Hovercraft, reconnaissance	13/02
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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and governmental concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

In the event of hazardous substance spill incidents and releases, first-hand accurate knowledge of the situation is vital. Obtaining that information, so that corrective actions can be implemented, is often dangerous and difficult because of the very nature of the prevailing hazardous conditions. This report documents one means of circumventing these obstacles and obtaining the information needed to plan corrective measures without risking the lives and health of those involved or increasing the risk of fire, explosion, and dispersion into environment. The proposed remotely controlled hovercraft, which employs highly sophisticated technology and is suitable for operation in antagonistic environments, may be a preferred information-gathering device for certain spill/release incidents.

Francis T. Mayo
Director
Municipal Environmental Research

ABSTRACT

The program was undertaken to prepare a conceptual design for a remotely controlled reconnaissance vehicle for use in hazardous substance spill or release environments and to assemble and test a much simplified prototype.

Data from past hazardous material spills experiences were analyzed to define the type of vehicle best suited for the reconnaissance duty and the vehicle's required performance standards. Based on the environmental conditions present at a "typical spill," the desired vehicle capabilities, and the level of operator skill that could reasonably be expected, the vehicle selected was a ground-effect machine or hovercraft. A skirted-hovercraft design was selected over a peripheral-jet version because of power requirements. The body of the proposed 8-ft diameter, 300-lb craft would be fabricated as a sandwich composite, using Nomex™ honeycomb filler between Kevlar™ face-sheets to provide high strength and an acceptable stiffness-to-weight ratio. High technology, but state-of-the-art, batteries and electric DC motors can drive a propulsion system that would give the vehicle an estimated 1.5-hr in-flight endurance at maximum power output and an effective operating range of one-half mile. The design also incorporates a television camera (visible, IR or UV) and a variety of optional gas sensors for remote reconnaissance of a spill area. Using only a 4 HP engine, the prototype craft is designed to clear obstacles approaching 18 in. in height. Greater heights could be surmounted by changed design and acceptance of shorter reconnaissance periods, i.e., operating at higher output from the batteries.

This report was submitted by the City of Oxnard and its subcontractor, Developmental Sciences, Inc., in fulfillment of Grant No. R-805365. The report covers the period of August 24, 1977 to September 8, 1978, and work was completed as of March 1979.

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SECTION I

INTRODUCTION

In recent years, hazardous material spills and releases have occurred at an increasing frequency, with concomitant loss of life, injuries, and major property damage. Among the common spills are releases of ammonia and chlorine, as well as hundreds of other substances classified as hazardous by virtue of their toxicity or flammability. These spill incidents occur at stationary or mobile sources due to a variety of causes including tank deterioration, transportation accidents (rail, water, and highway), and human error.

Hazardous substance spill prevention is primarily the responsibility of the private sector. When an incident occurs that overwhelms the capabilities of the private parties then the local fire department and other public agencies are often called upon to assist in protecting the community. In many cases, the local fire departments are not prepared to cope with toxic material spills, particularly when these are large.

Many spills and releases are initially of undetermined nature and/or exact origin, because of low visibility due either to a chemical haze caused by the spill itself or to obstructions at the site. The determination of the nature and source of the spill is the critical first step in controlling the situation and often involves considerable risk to on-site personnel. It is undesirable to send anyone into an area of unknown hazard, and EPA recognizes the need for a remotely operated device that could be sent into a spill area to provide the responding personnel with:

1. Information on the nature of the spill

2. A means of stopping or neutralizing any leak or other release path.

As part of its overall approach to the hazardous materials spill problem, the EPA awarded a grant (R-805365) to develop a remotely operated device for spill investigation and control to the City of Oxnard, California. Oxnard is located approximately 60 miles northwest of Los Angeles in an expanding urban community. This area is the center of growing industrialization with facilities manufacturing, using, and storing large volumes of oils, fuels, chemicals, explosives, agricultural chemicals, etc. Several major freeways, carrying a high volume of truck traffic transporting chemicals and explosives pass, through Oxnard's boundaries. There is also a Southern Pacific Railroad line. More than 20% of Southern Pacific's business is hauling chemicals.

Thus, Oxnard can be considered representative of the many and varied areas with significant hazardous material spill potential. Oxnard is a microcosm of potential spill situations and because of its progressive fire department, Oxnard was considered to be an ideal participant in the development of new technology to combat spills.

The City of Oxnard selected Development Sciences, Inc., City of Industry, CA, as its prime contractor to perform the technical work of this program. DSI is a small, technically flexible firm with extensive experience in the development of unmanned vehicle systems.

PROGRAM GOALS AND TASKS

The ultimate goal of the program was the design of a device that could be remotely operated in a hazardous environment. In order to achieve this goal, data, and experiences from past hazardous material spills were collected, reviewed, and analyzed to aid in defining vehicle performance requirements and desired vehicle characteristics. Various options for propulsion, payload, structure, materials, etc. were evaluated, and the trade-offs and impacts of different decisions on vehicle performance and cost were considered. An intermediate goal was the design, fabrication, and operation of a 1/2-scale model of the system that could be used to demonstrate feasibility.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

A remotely operated vehicle that could be sent into a hazardous spill area, or uncontrolled waste site, would be a valuable tool with which to gather initial information prior to site entry by field response personnel. Site reconnaissance is the single most valuable function that a remotely operated vehicle can perform.

A ground-effect machine (GEM) or hovercraft offers the best compromise of capability and cost for remote reconnaissance. Of the two types of hovercraft, skirted and peripheral-jet, the skirted configuration was selected as requiring the lower power. The light weight of the hovercraft, while necessary for maximum effectiveness in reconnaissance, precludes the use of remote manipulators or other devices on an airborne vehicle for initial spill mitigation efforts. The different requirements for control or mitigation of individual spills under different, unique field conditions also make it unlikely that the addition of a single manipulator arm would be of much benefit. The major problem is that every mechanical action (valve turning, manipulator functions) is accompanied by an equal and opposite reaction (Newton's third law), which can only be provided by highly controlled counter-thrusting.

Other candidate vehicles evaluated for remote-controlled operation included ground-based vehicles and free-flying craft. Ground-based vehicles were rejected because of their inability to traverse large muddy areas and obstacles without contact. Free-flying craft such as helicopters were considered unsuitable due to the complexity of the on-board stabilization equipment required and their low payload capacity relative to hovercraft. The use of radio-guided "model" airplanes have the disadvantage of being unable to hover or to move at very low speeds, such as are necessary for reconnaissance at short distances. Lighter-than-air crafts (blimps) were also considered, but not evaluated in depth. An advantage is the capacity to operate at greater heights, but there are significant problems in maneuvering a blimp and in maintaining a stable position in the presence of breezes and up- and down-draft situations. A more thorough assessment may better define the capabilities and trade-offs.

Optimum design of the remotely controlled hovercraft requires that the vehicle (1) pose no risk of ignition in an explosive atmosphere, (2) be resistant to an antagonistic environment, (3) require minimum operator

skill while maneuvering under remote control, and (4) be able to transmit considerable information to a nearby command post. A Kevlar shell and Teflon™ film coating provide the needed corrosion protection, and remotely controllable, battery-powered electric motors and a television camera satisfy the maneuvering and observation requirements. Several different types of gas sensors can also be added to the craft with minimal penalty in weight.

The estimated cost for a fully operational prototype of the skirted hovercraft with all necessary equipment for use in remote reconnaissance work is $322,000 (1978). Operating cost is estimated at $2,000 to $3,500 per mission.

Before initiating a program to construct a full-scale, prototype vehicle, a smaller and less sophisticated half-scale model was designed, fabricated, and operated to establish the feasibility of the concept.

Because of funding limitations, no work beyond that reported herein could be undertaken.

SECTION 3

DEFINITION OF VEHICLE DESIGN OBJECTIVES

A program was undertaken to identify release and spill site characteristics that could contribute to the design of a spill assessment vehicle. Existing documentation on hazardous material spills, including "incident reports" published by such bodies as the National Transportation Safety Board and the Department of Transportation, provided only limited help toward defining the characteristics and capabilities of a remotely operated vehicle for spill investigation and control. Discussions with personnel involved in fire protection and spill control identified several problems frequently faced by these workers, such as the different types of terrain and the obstructions, both natural and those resulting from spill causes (e.g., twisted piping or rails, upset vehicles, etc.) that had to be traversed in reaching a spill for examination or corrective action; limited visibility for observation of the site from a safe distance due to chemical fumes, hazes, smoke, etc.; and the assurance that any equipment used did not create additional hazards. In addition, these discussions identified a range of equipment that would be useful in the evaluation or correction of a spill or release situation.

Based on an analysis of the information developed, a number of basic conclusions or design objectives were reached about the desired vehicle characteristics and capabilities. These follow:

1. The vehicle must in no way accentuate the existing hazard; this constraint applies most directly to the necessity of not introducing any source of ignition into what may possibly be a flammable and/or explosive environment.

2. The vehicle should have a range of approximately one-half mile (from the command post) and an endurance of approximately one-half hour.

3. The vehicle should be able to traverse a 20^{o} (or roughly 1:4) slope and 18-in.-high obstacles.

4. The vehicle should be no more than 8-ft wide (for transportability) and at least as maneuverable as a subcompact automobile.

5. Operator skill requirements should be relatively low--similar to those needed to drive an automobile.

6. Maintenance and repair requirements should be minimal.

7. Reliability and quick response at the spill site are essential.

Furthermore, it was generally agreed that remote reconnaissance was the single most desirable capability for the device. The ability to provide remote chemical analysis was considered to be a valuable adjunct to reconnaissance. This could range from having relatively simple sensors (such as currently available explosion meters, hydrogen meters, etc.) on board and transmitting the readouts back to the command post to providing the capability to obtain and return samples to the command post for subsequent analysis and, ultimately, to carrying a lightweight mass spectrometer on the vehicle. (Such an instrument is, to our knowledge, not yet commercially available.) While the ability to perform some sort of mechanical spill-mitigating task would be a definite plus, it was recognized that corrective measures vary so much from spill to spill that a single manipulator arm would not be of great benefit. Therefore, spill-mitigating capabilities were deemed to be of lower priority and were not included in the design objectives.

Many of those with whom the concept was discussed thought of a remotely operated device as most useful as part of a "set" of specialized spill control equipment items to be used by fire department (or private industry) personnel with special training in the techniques of responding to hazardous material spills and releases.

SECTION 4

VEHICLE SELECTION

CANDIDATE VEHICLES

Ground-based Vehicles

The first family of vehicles one might consider for spill investigation is ground-based vehicles, i.e., all manner of wheeled, tracked, or even "walking" vehicles. A number of remotely controlled ground-based vehicles exist, e.g., the SNAIL, the FIRECAT, and the WHEELBARROW. The SNAIL and the FIRECAT are tracked vehicles used primarily to drag fire hoses or to apply foam or other agents. The WHEELBARROW is used by bomb squads for deactivating packages suspected of containing explosives; it is a tracked vehicle equipped with a closed-circuit TV system. The primary shortcoming of these vehicles is their inability to traverse large "muddy" areas such as may be caused by a large-volume spill. In addition, they currently are not constructed of materials that would allow them to be used in a corrosive environment.

A more practical alternative vehicle may be a highly modified version of a commercially available all-terrain vehicle (ATV). These recreational vehicles (typically of one-to-four-passenger capacity) are highly adept at hill climbing and many are also amphibious. The vehicle used for spill investigation and control would, of course, have to be constructed of corrosion-resistant materials and have an "inert" propulsion system.

Ground-Effect Machines

The ground-effect machine (GEM) or more popularly, the hovercraft, is a device that rides on a cushion of air, much like the puck in a game of air hockey. A difference is that the hovercraft supplies its own air cushion by means of a lift fan (or fans) feeding the craft's "cushion" (Figure 1). Hovercrafts of various sizes are in operation today, from one-man recreational vehicles to multi-passenger, high-speed ferries.

The major attraction of the GEM for use in hazardous environments is the ability of the device to traverse a wide range of terrains with minimal contact with the ground. This reduces the degree of corrosion resistance that is required, and also reduces the risk of striking sparks (either through direct contact with hard objects or by disturbing existing metallic debris). The air that flows from the perimeter of the craft, is of low speed and does not substantially disturb the surrounding conditions.

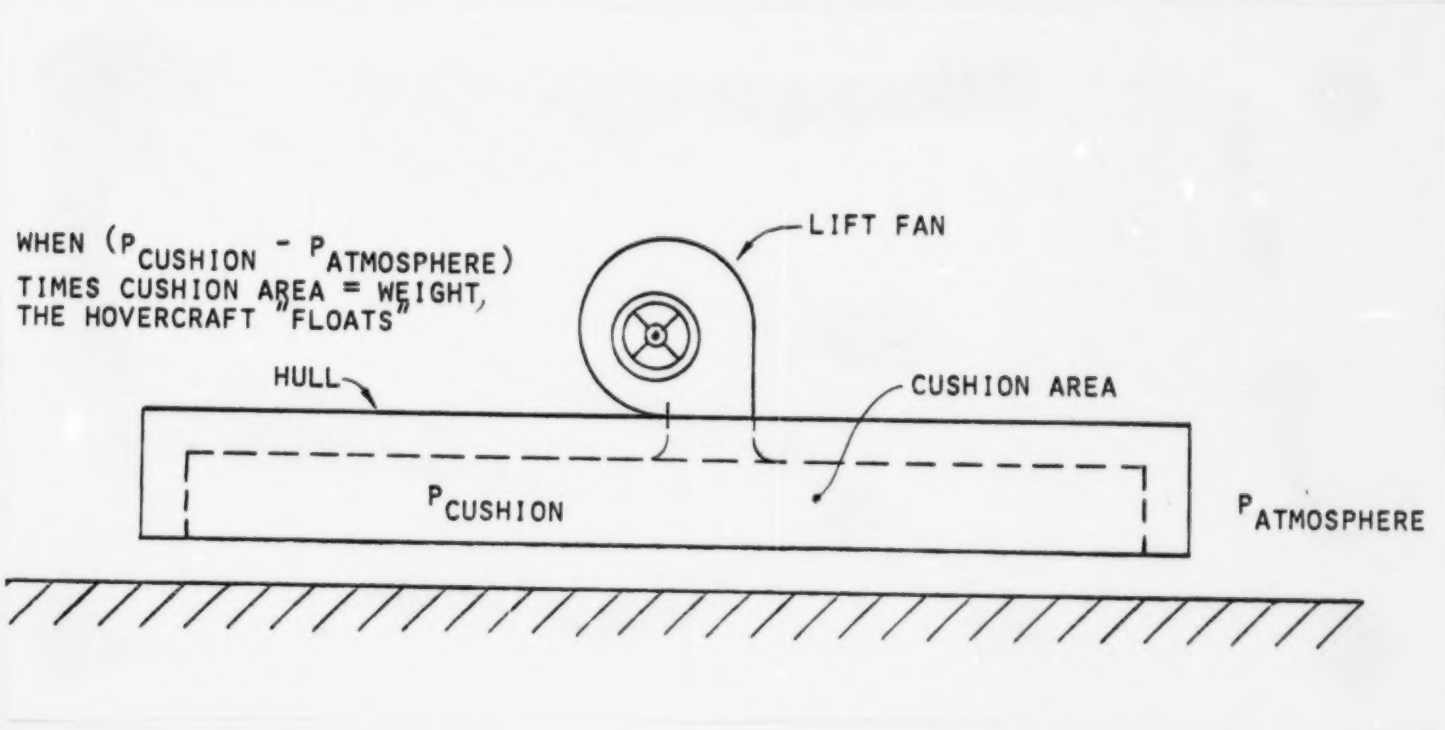


Figure 1. Simple hovercraft on air cushion.

Flying Vehicles

The third alternative is a free-flying vehicle. Here we refer not to a fixed-wing airplane, which must maintain substantial forward speed to sustain flight, but to a vehicle with hovering capability. A remotely-piloted helicopter, with its exposed rotors, would be an invitation to disaster in many hazardous spill situations, so a ducted rotor design would be necessary. Such a vehicle, with its ability to traverse any obstacle and hover for extended reconnaissance, would seem to be the ultimate for surveying a problem area, but it would provide little or no corrective capabilities, since it could not, in its hover mode, provide the reaction force needed for almost any mitigating activity. In addition the payload capacity of such a craft is very low and the downdraft created by its rotors could seriously disturb the spill site. Blimps (lighter-than-air crafts) have inherent disadvantages--in-place instability and poor flight control--and were not exhaustively evaluated. More detailed consideration of blimps is probably warranted.

VEHICLE ANALYSIS AND COMPARISON

Table 1 lists the major characteristics, the advantages, and the disadvantages for three types of vehicles considered. The characteristics are based on conceptual vehicles designed specifically for spill control and reflect advanced aerospace technology.

Based on the opinion of fire protection and spill response personnel (1) that initial spill-site reconnaissance is the most important function to be performed by such a vehicle and (2) that levels of complexity beyond the ability of most fire department personnel are to be avoided, the conclusion was that the hovercraft represents the best choice for a first generation vehicle. While the free-flying machine (helicopter) may offer the ultimate in reconnaissance capability, the complexity (and hence, cost) of the device, coupled with the high level of operator skill required (even with a "smart" on-board autopilot), effectively eliminates this class of vehicle from consideration. On the other hand, the ATV, although it possesses the potential to carry a much greater payload for the same power, must travel "through" the spill, rather than over it. The ATV may become an addition to the spill-fighting equipment inventory at a later time, in the role of mitigator rather than investigator, which would better utilize the particular strengths of this type of vehicle. (Blimps were not characterized).

TABLE 1. CHARACTERISTICS OF THE THREE CANDIDATE VEHICLES

Characteristic	Ground-based vehicle	Ground-effect vehicle	Free-flying craft
Total weight	800 lb	300 lb	110 lb
Power required	10 hp	15 hp	15 hp
Payload capacity (incl. TV camera)	300 lb	50 lb	15 lb
Maximum velocity	15 fps	10 fps	20 fps
Maximum grade	40°	20°	--
Maximum crosswind	50 knots	25 knots	15 knots
Maximum obstacle size	15 in.	18 in.	--
Major advantages:	Relatively low cost Large payload Simple control Able to "idle" in place	Minimal ground contact Able to "idle" in place	Can provide overview of spill site Least contact with spill Can traverse all obstacles
Major disadvantages:	High corrosion resistance required Most contact with spill Can't go over large obstacles Limited camera height	Lower payload than ATV Relatively complex autopilot Can't go over large obstacles Limited camera height Can't traverse open grates	Very Complex autopilot High cost Low payload Most susceptible to crosswinds/gusts Downdraft can spread spilled chemical

SECTION 5

VEHICLE SUB-SYSTEM OPTIONS

PROPULSION OPTIONS

The single, most demanding constraint on the choice of a propulsion system for the spill vehicle is that it must not add to the potential hazard at the spill site. This basically means that the vehicle must not use motors or engines that can provide an ignition source (such as sparking at ignition contact points or a hot exhaust system); consequently a standard internal combustion engine is immediately eliminated. Specially built IC engines remain candidates but may always have unacceptable power-to-weight ratios. Four candidate "safe" propulsion systems were evaluated.

Pneumatic Motors

Pneumatic motors have long been used in hazardous environments--specifically, as a source of power for hand tools in coal mining operations. The one main drawback of this type of power unit is the low energy density of the "fuel". Assuming perfect isothermal (constant temperature) expansion of nitrogen gas* from 3,000 psi to ambient pressure, only about 60 watt-hours per pound of "fuel" is available, not including the weight of the tank. When tank weight is factored in (assuming a tank weighing at least five times as much as the gas it contains, for the size tank required for this mission), the energy density is only about 10 watt-hours per pound, which is not sufficient. Little is gained by increasing the pressure of the compressed gas, since the weight (thicker steel cylinder walls) of the tank also increases.

Liquid Nitrogen Motors

Considerable research has been conducted by the British Mining Research and Development Establishment and by the University of Nevada at Reno on the development of a liquid nitrogen power unit. The principle of operation is similar to that of the common steam engine, with liquefied nitrogen (LN_2) replacing water as the working fluid and ambient heat replacing the boiler as the heat source.

*Nitrogen would be used because it is essentially inert, while compressed air is roughly one-fifth oxygen.

This scheme has several intriguing characteristics, namely:

1. The engine actually removes heat from its environment, rather than adding it;

2. The engine's exhaust is nitrogen gas, which does not contribute to the hazard;

3. The engine's internal friction generates heat and is an aid to the expansion of the N_2 gas, so that additional work is extracted from an otherwise objectionable engine characteristic (frictional heat energy losses);

4. The engine's exhaust can be ducted throughout the vehicle for cooling purposes;

5. Surplus fuel could be used to extinguish small fires or freeze the leak; and

6. Power sources up to 7.5 kw have been built and operated.

Although the energy density is greater than that available with compressed gaseous nitrogen (energy densities of about 90 watt-hours per pound have been attained), the handling and long-term storage of LN_2 are not simple and the vehicle would require the insulation necessary for maintaining the extremely low temperature of LN_2--a cumbersome requirement.

Monopropellant Engines

An alternate source of power widely used by the military is a monopropellant engine. In these systems, a monopropellant such as hydrogen peroxide or hydrazine is catalytically decomposed to form hot gas, which is used to drive a piston expander, a turbine, or a sliding vane motor. The monopropellants such as hydrazine, nitromethane, n-propyl nitrate, and 90% hydrogen peroxide are all readily available. All of the hydrogen-containing compounds, except hydrogen peroxide, are explosive and may prove to be dangerous if fumes escape. In the absence of organic matter, hydrogen peroxide is relatively safe and widely used in industry.

Therefore, it is likely that a monopropellant engine to be used in a hazardous spill environment would be powered by hydrogen peroxide in the interest of safety. It is relatively stable and requires a catalyst to make it decompose to water, oxygen, and heat. The cost of 90% hydrogen peroxide is about $0.70/lb.

The major drawbacks of using any monopropellant engine are: (1) the need to sufficiently cool the exhaust gases to eliminate the chance of igniting any flammable liquids or gases the vehicle may encounter, and (2) the extensive development necessary to adapt existing monopropellant powerplants to the proposed vehicle system. The hydrogen peroxide propellant would also enrich the ambient air in oxygen, which may be undesireable.

Electric Power

The use of electric power for a non-ground vehicle was initially thought to be unrealistic due to both the low energy density of standard batteries (50 to 70 watt-hours per pound was a commonly advertised maximum) and the low power-to-weight ratios of standard DC electric motors (from 7 to 20 lb/HP. typically). However, recent advances in both battery and motor technology, spurred by NASA-sponsored programs such as the Mars "Sniffer" airplane have made electric propulsion a very attractive alternative for the near future. The costs, currently quite high because of limited production, will almost certainly decrease as earth-bound uses for these advanced products proliferate.

Recent developments have produced primary (non-rechargeable) batteries with energy densities of 300 watt-hours per pound. Even more encouraging is the fact that this has been achieved despite the need for relatively heavy battery case structures. The energy density of the core materials is on the order of 550 watt-hours per pound. Light-weight graphite composite battery cases that are expected to yield package energy densities on the order of 450 watt-hours per pound, with maximum drain rates of roughly 300 watts per pound, are currently being developed.

Complementing these advances in battery technology are the recent strides in DC electric motors. The present state of the art is the selenium-cobalt motor being developed and built by a number of companies, including Garrett, North American, and Sunstrand. These motors are brush-less and, therefore, present no danger of ignition of a spill through sparking. They also possess extremely high power-to-weight ratios (on the order of 1 HP/lb including a gear reduction unit) and good efficiency (82 to 87%, depending on power and gear reduction).

Using both state-of-the-art batteries and motors, only 3 lb of batteries and 1 lb of motor mass are needed for each horsepower required. This 4 lb/HP ratio is based on an assumption of maximum power consumption, which will be the case for only a small percentage of the time for a typical spill scenario. Given the favorable power-to-weight ratios of this combination plus the inherent safety, reliability, and simplicity of control for brush-less DC motors, this option appears to be the best choice for the proposed vehicle.

RECONNAISSANCE OPTIONS

The vehicle will perform its remote reconnaissance function by transmitting video or bringing information about or returning actual gas samples or gas analysis tubes (Orsat, MSA) from the spill site to the operator at a nearby command post. Several options, based on equipment currently available or under development, have been considered for incorporation in the vehicle. Cost, weight, lighting conditions, and video image or data quality are some of the factors taken into account. As described later in this report, the imaging system selected will be used to direct the movement of the vehicle, as well as to observe the spill site.

Observation System Options

Television--

The simplest form of observation would be performed using a standard television camera with provisions for remote aiming and focusing. A monitor on the control console would show a TV image of the scene. On-board illumination could be provided to augment (or replace) ambient light.

Forward Looking Infra-Red (FLIR)--

Several companies in the U.S. have been under military contract to develop compact, lightweight FLIR units. Although costs are still quite high (FLIR units are still in the prototype stage), FLIR units can be obtained. The average weight of a FLIR unit including pan and tilt gimbal is about 20 lb.

The FLIR has the advantage over conventional TV in that no visible light is required for its operation. Additionally, the FLIR offers substantially better penetration through fog and haze than conventional TV. Inquiries were made to Honeywell and to Ford Aeronautronics (manufacturers of mini-FLIRS) regarding the ability of these units to penetrate various gases commonly associated with hazardous material spills. Unfortunately, little information is available on gases other than air or air-aerosol mixtures and specific tests would be required.

Radar Imaging--

At the present time, imaging radar systems are not available in a package that would be suitable to the hazardous spill vehicle application. Present systems, aside from being very large and heavy, have relatively poor resolution and are designed specifically for long-range applications.

Sonic Imaging--

As is the case with radar imaging, acoustic (or sonar) imaging systems have yet to reach the level of refinement (and perhaps even more important, miniaturization) necessary for use in this particular application. While a relatively simple ultrasonic rangefinder (such as that used on Polaroid's new auto-focus camera) may be a useful addition to the vehicle (to warn of an impending collision), the resolution necessary for detailed imaging has not been attained. Furthermore, the question of the effect on performance of absorption of the sonic waves by any smoke or haze particles remains unanswered.

Imaging System Selection

Television systems offer the highest resolution of all candidate imaging systems (up to 1,000 lines for a daylight camera and 600 lines for a low-light-level device). Intensified target tubes allow operation under very low light levels (10^{-3} to 10^{-6} foot-candles scene illumination). These cameras can be very compact and are probably the best suited (at least in initial applications) to the vehicle under consideration. Color TV has some advantages, but cannot operate at as low light levels as black and white.

The camera would be mounted on a pan/tilt gimbal providing 360° azimuth and +60° to -30° elevation coverage. The gimbal would be stabilized in the two actuation axes with an accuracy of approximately 5 milliradians. A motorized zoom lens with a field of view varying from 60° to 6° would also be desirable. At the narrowest field of view, an object of less than 1 in. in size (minimum dimension) could be identified at a distance of 50 ft.

Data-Gathering Options

Gas Sensors--

A number of small sensing units are on the market, allowing detection of a wide range of gases. (Most units actually measure only one gas, or a family of gases, such as hexanes.) The typical meter readout is in parts per million (ppm) of the gas, or sometimes, in percentage of the lower explosive level (% LEL). This latter is, in effect, an "explosion hazard" meter.

Since most of the commercially available gas detectors and explosion meters are compact and lightweight (designed for one-hand carrying and simultaneous reading), a number of units could be carried by the spill vehicle and their outputs transmitted back to the control console. It would even be possible to modify the sensing units to a plug-in module format, in which case the On-Scene Coordinator could select several sensing units from his total group (of perhaps ten) to send in with the craft.

A second type of gas detector utilizes sealed cartridges of crystals with known sensitivity to certain gases. (Again, each crystal type is sensitive to only a single gas.) When gas is drawn through the cartridge at a specific rate, the crystals change color, with the degree and amount of discoloration indicating the amount of the specified chemical present in the air. This type of detector must be returned to the operator for inspection, which introduces an undesirable time delay; however, on the other hand, no electrical power is consumed (except for the pump that draws the gas/vapor sample over the crystals) and no telemetry of data is required. This detector type is an averaging-type sensor and does not provide information about varying concentrations of the substance around the spill site.

The third means of determining atmospheric content (or, for that matter, the nature of streams or puddles of chemicals) is the "sample-return" technique. On-board devices could take samples of gases or liquids and return them to the command post for comprehensive chemical analysis.

Of the three methods, only the on-board, remote readout units can provide "mapping" of gas concentrations and aid in the location of the leak through "homing." Therefore, it is judged that the meter-type sensors (with remote readout) provide the best means of determining atmospheric composition in this application. The following substances (among others) could be monitored: hydrogen, hexanes, ozone, chlorine, fluorine, ammonia, propane, butane, sulfuric acid, nitric acid, and hydrochloric acid.

COMMUNICATION OPTIONS

For any remotely operated device to be effective, two-way communication with the command post is essential. For the reconnaissance application, there are two options available for providing a command link (to the vehicle) and a data link (from the vehicle)--either a radio frequency (RF) link or a trailing-cable umbilical link. Each method of maintaining contact with the vehicle has its advantages and disadvantages.

Radio Frequency Links

The use of RF for the command and data links allows the vehicle to be completely unencumbered as it maneuvers around the spill site. The danger of loss of signal due to damage to a trailing cable is also eliminated. However, RF links are not without their problems. The greatest weakness of RF communication is simple shielding - blockage of the radio waves by obstacles. Obstructions such as buildings, large storage tanks, etc. could interfere with the signal.

This obstruction problem increases as transmission frequencies increase. Thus, the (relatively) low frequencies required for command links and, for example, gas sampler data links would be unaffected by the type of obstacles around which the craft would be required to maneuver. However, the degree of resolution (500 to 1,000 lines) required for a TV imaging system (in our case, low-light-level black and white TV) requires a frequency bandwidth of 3-5 MHz and up to 10 MHz for color TV). A standard VHF RF link will provide this bandwidth, but adequate system performance depends on line-of-sight being maintained between the command post and the vehicle. (The alternative of dropping signal "repeaters" along the vehicle's route to maintain contact adds both cost and complexity to the system that far outweigh the advantages gained).

It is possible to reduce the bandwidth required (thus lowering the broadcast frequency and reducing the chance of signal blockage) by changing from "real-time" imaging (which has an image refreshment rate of 30 times per second) to "stop-action" imaging (with a refreshment rate of only 2 or 3 times per second). This would reduce the required bandwidth by an order of magnitude. The use of slow-scan imaging has proven useful in many applications, but, in this particular case, the distraction to the operator caused by the more jerky representation of vehicle motion, as well as the reduced resolution of moving objects, outweighs the advantage.

Hard-Wire Links

The use of hard-wire umbilicals for control and/or data retrieval, while immune to the problem of signal shielding, presents some unique problems. Foremost is simply the complication to vehicle maneuvering that is introduced by the presence of the cable. The cable cannot merely be dragged by the craft, since this would result both in a loss of vehicle control and maneuverability and in the danger of severing the umbilical.

The alternative is to carry the cable on the vehicle and pay it out as the vehicle moves about. This entails carrying approximately 50 lb of cable and spool on the vehicle. In addition, cable still is exposed to possible damage or contamination and, following the mission, may need to be replaced, and therefore becomes a costly expendable.

The only task for which a hard-wire link is justified is the transmission of the video signal from the vehicle. Since only one conductor is necessary, co-ax cable weight would be greatly reduced. The hard-wire link could be a back-up for the video RF link. The spool of cable could be installed on the vehicle prior to any mission that appeared to have a potential for loss of RF signal.

A good example of a cable suitable for carrying the video signal back to the command post is RG1788/U, a miniature co-axial cable. Both the dielectric and outer jacket are Teflon. The cable is weatherproof and chemically inert (due to the Teflon jacket) and will operate continuously at 250°C (480°F). The cable has an outer diameter of 0.075 in and weighs 4.26 lb per 1,000 lineal ft. Hence, 3,000 ft of cable weighs less than 13 lb and would require only three layers on a 1-ft dia. x 2-ft long spool. The spool, cable, and connectors for this system could thus weigh less than 15 lb. The cost for this single-channel cable is 5 to 7 times less than the cost of a multi-conductor control/data cable, and, since it would not be required for every mission, use of this cable is easily justified by the advantages it affords.

SECTION 6

PROTOTYPE VEHICLE CONCEPTUAL DESIGN

BASIC VEHICLE CONFIGURATION

Based on the analysis of spill data, the vehicle type selected for this application is the ground-effect machine, or hovercraft, as described in Section 4.

The two basic configurations for hovercraft are the peripheral-jet hovercraft (Figure 2a) and the skirted hovercraft (Figure 2b). Given sufficient power, peripheral-jet hovercraft can rise out of ground effect made into free flight. The levels of operator skill and control system sophistication required for vehicle stabilization may exceed the advantages gained from free-flight capability. In the absence of the need for out-of-ground-effect operation, the peripheral-jet hovercraft has one major drawback when compared to a skirted hovercraft--considerably more power is required to obtain sufficient height to clear sizable objects. Figure 3 shows the minimum lift power required (excluding power for stabilization) as a function of vehicle weight for different ground clearances for an 8-ft diameter peripheral-jet machine. It can be seen that for a vehicle in the 300 lb class, about 15 HP is required to clear an 18-in obstacle.

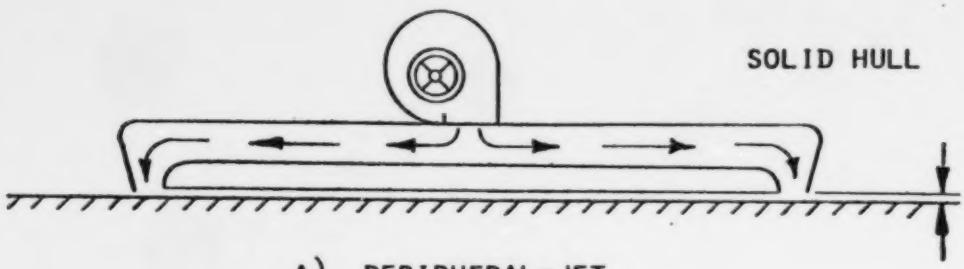
For the type of powerplants suitable for operating in a hazardous spill environment, it is desirable to limit the installed power to values lower than this. For example, 5 HP would probably be considered a maximum reasonable value for the lift fan of an electric-powered vehicle in this weight class. Based on Figure 3, this would allow maximum ground clearances of only about 7 in. for the peripheral-jet vehicle.

The use of a flexible skirt as shown in Figure 2b instead of a peripheral-jet allows the craft to pass over substantial obstacles without the need for the large, power-consuming "daylight" clearance necessary in a peripheral-jet machine. For this reason, virtually all ground-effect machines in operation are of the skirted type.

Precise power requirements for skirted ground-effect machines are more difficult to determine, as they are affected by skirt design. A semi-empirical correlation based on existing machines is given below:

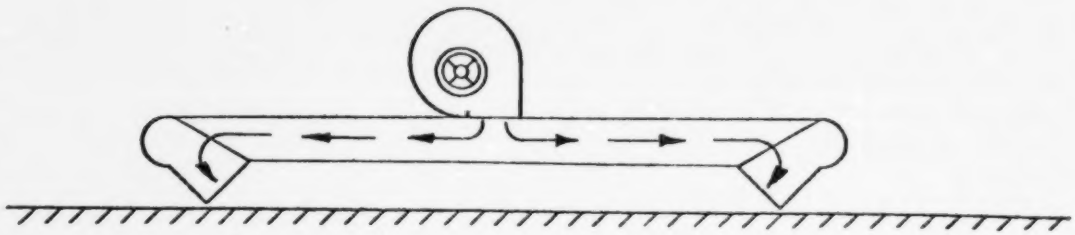
$$(\text{LIFT HP})_{\text{req.}} = 0.030\ W^{3/2} / A$$

where W is the vehicle weight (lb), and
A is the cushion area (ft^2)



A) PERIPHERAL-JET

HEIGHT OF DAYLIGHT GAP MUST AT
LEAST EQUAL OBSTACLE HEIGHT



B) SKIRTED

SKIRT DEFORMS TO ABSORB OBSTACLES UNDER
CRAFT W/O LARGE DAYLIGHT CLEARANCE

Figure 2. Basic peripheral-jet and skirted hovercraft concepts

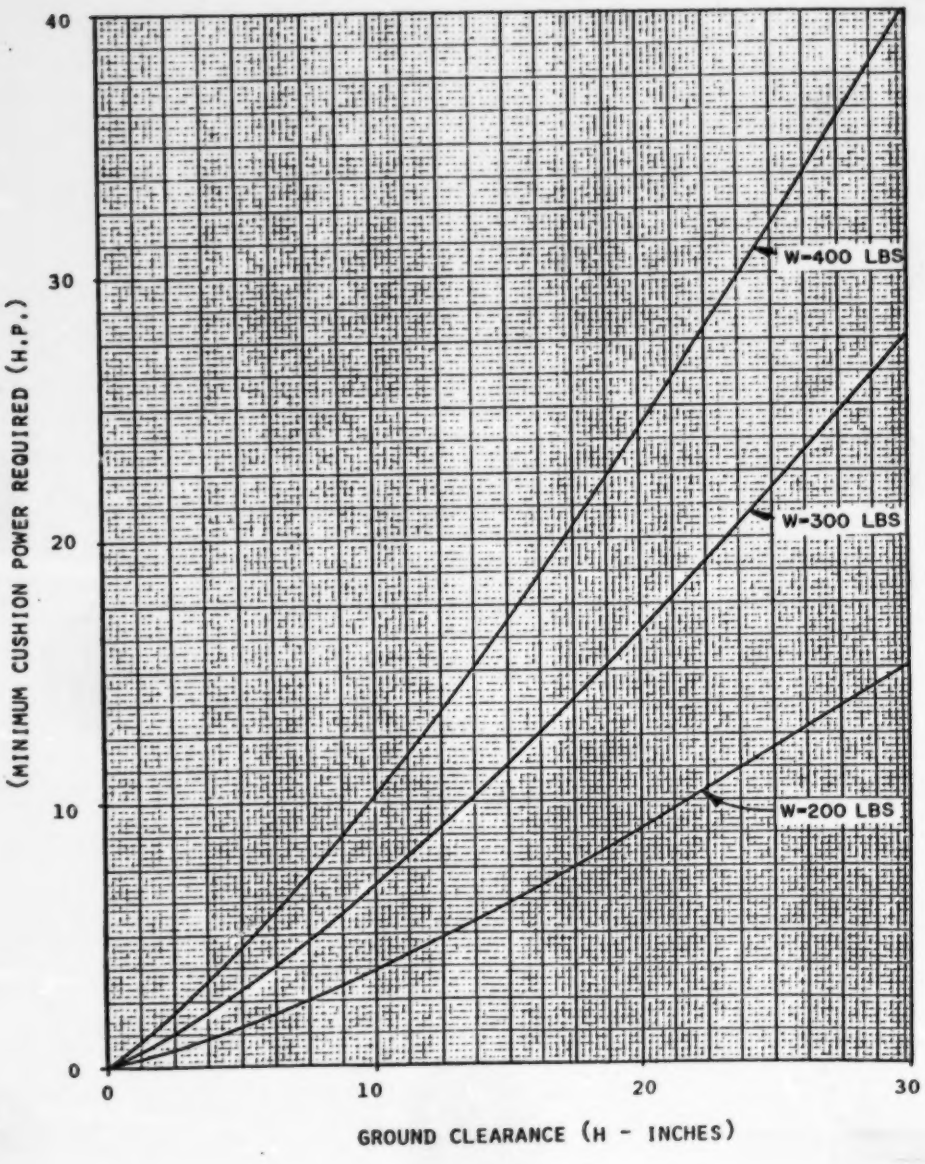


Figure 3. Cushion power requirements for peripheral-jet ground effect machine.

For an 8-ft diameter machine (with a cushion diameter of 7 ft) weighing 300 lb, the cushion power required would be about 4 HP. With proper design, the skirt depth can be made as large as 20% of the diameter before stability problems and other difficulties are encountered. With a properly designed skirt system, the skirted ground-effect machine can pass over objects very nearly as high as the skirt depth. Thus, the 300-lb, 8-ft diameter skirted vehicle discussed above should be able to clear obstacles approaching 18-in. in height using only 4 HP, as compared to the 15 HP needed for the peripheral-jet system to clear the same sized obstacle.

Additionally, because of the larger cushion power levels associated with the peripheral-jet GEM, considerably more sprav is generated over liquid surfaces than with the skirted GEM, a decidedly undesirable feature in a hazardous spill environment.

Given that the vehicle is to be of the skirted hovercraft type, the basic vehicle shape remains to be chosen. Most existing hovercraft are basically rectangular with a semi-circular front. A lift fan (or fans) provides air to the cushion area, while a thrust fan (or fans) provides forward propulsion, with steering provided by rudders aft of the thrust fan(s). This configuration is best suited to relatively high-speed operation (15 mph and up, as is the case with most existing designs).

The present application, however, requires a relatively low top speed (probably no more than 6 to 8 mph) and extensive low-speed operation (speeds ranging from a complete stop to only 1 to 2 fps (0.7 to 1.4 mph)). In this type of operation, the principal advantage of the hovercraft (its ability to "float" above the ground) introduces a complication--the vehicle is susceptible to the slightest side-force. Either crosswinds or operation on sloping ground will tend to introduce sideslip, representing a substantial percentage of the forward velocity, into the vehicle's motion Hence, the direction and magnitude of thrust must be chosen to provide the movement required and to cancel any extraneous forces acting on the vehicle. Since the direction of thrust is not necessarily coincident with the direction of motion, a circular shape is preferred to avoid requiring the vehicle to negotiate a narrow clearance "sideways", i.e., across the long dimension. With a circular vehicle, a single, centrally located, axial blower (driven by an electric motor) represents the best choice for the lift fan. Figure 4 includes two views of such a skirted hovercraft vehicle. By flanking the lift fan intake duct with a pair of 20-in. diameter variable/reversible-pitch ducted rotors driven at constant rpm by electric motors, near-instantaneous changes in both thrust/braking and yaw movement can be provided . (The vehicle is yawed by setting the two rotors to different pitch settings.) The imaging system tower would extend upward above the hub of the axial lift fan for unobstructed viewing around the vehicle.

VEHICLE STRUCTURE

The craft would be of sandwich panel construction, using Nomex honeycomb between Kevlar face-sheets. The process for manufacturing this type of structure has been developed and refined by DSI in its remotely piloted

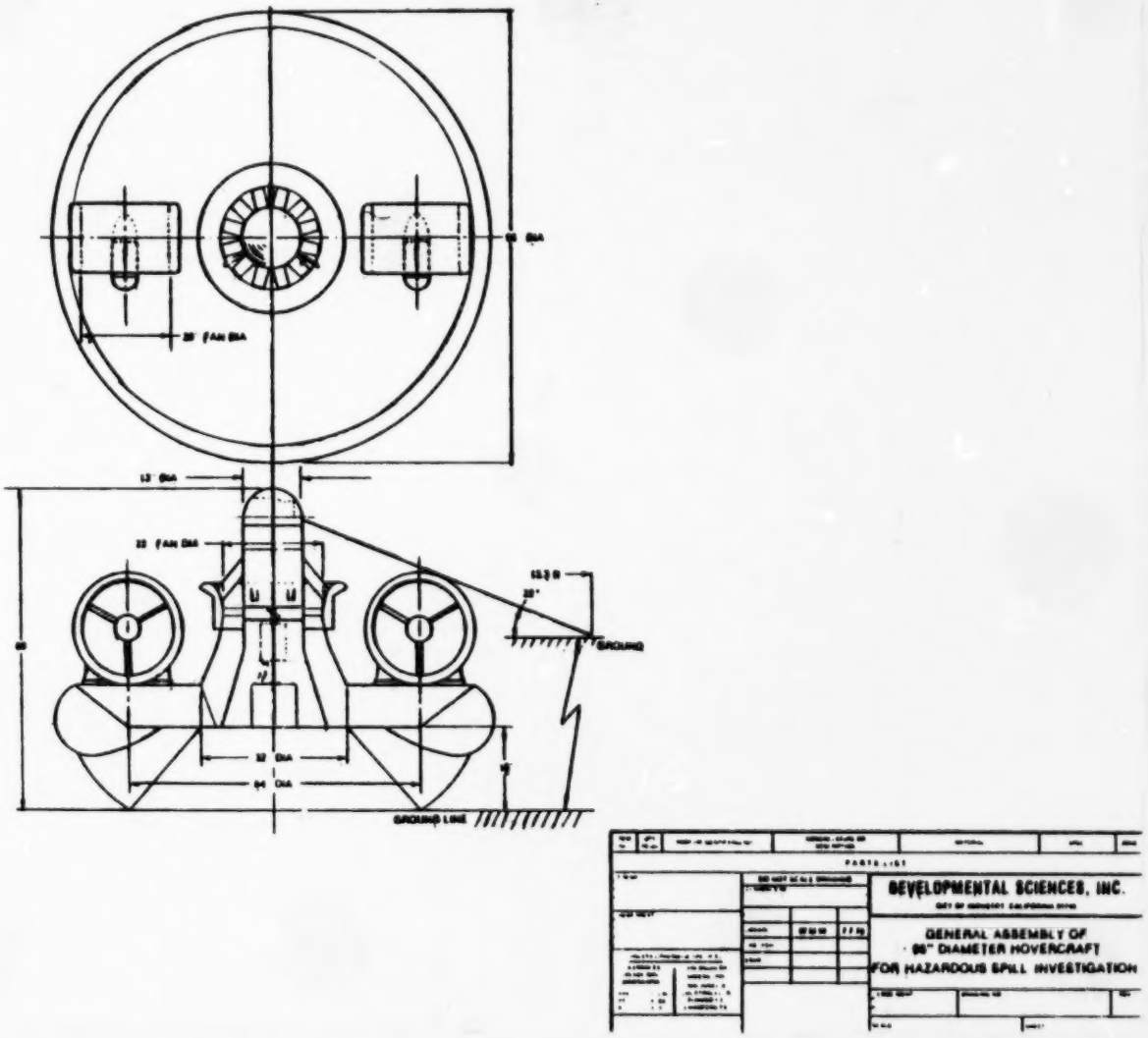


Figure 4. Schematic of skirted hovercraft.

aircraft programs for the military. Extremely high strength and stiffness-to-weight structures are achieved with these methods.

The surfaces likely to be exposed to hazardous materials would be film-coated with a chemically inert material, such as Teflon.

VEHICLE SKIRT DESIGN

To best satisfy the mission requirements, a basic bag and finger skirt system has been selected for the following reasons:

* The basic bag-and-finger skirt is the simplest and best proven system in current use.

* As designed for this application, it will be possible to modify the skirt if initial tests indicate such a requirement.

* The system is one of the least expensive to design, fabricate, install, and maintain.

* The basic design will be relatively insensiitive to air pressure and air flow rates induced by the lift fan.

The bag and finger skirt system configuration selected for this application is comprised of (1) a full peripheral bag consisting of an inner and outer loop section; (2) a continuous series of 60 open fingers; (3) a series of six baffles to compartmentalize the bag. Air-feed holes are cut in the inner loop over each finger section. The "bag" formed by the inner and outer loops is partitioned in six places to match the vertical structural stiffeners dividing the upper and lower decks of the craft. The partitions, simple fabric sections cut to the shape of the inflated bag and hull shape, are continuously attached to both the bag and hull vertical stiffeners. Air from the lift fan is equally distributed into the bag through each of the six compartments formed between the vertical stiffeners and the upper and lower decks. The air then bleeds through the holes in the inner loop through the fingers to pressurize the cushion.

A ratio of approximately 55% for the finger height to cushion height was selected with approximately a 45 degree finger-to-surface angle. This arrangement allows for the maximum cushion area while retaining good roll/pitch stability. The purpose of compartmenting the bag becomes apparent when the craft is considered to be rolling/pitching in such a manner as to close off the feed holes to the cushion (i.e., the fingers are fully collapsed). The compartmented bag will build up pressure and increase restoring force, thus restabilizing the vehicle. Should this restoring force prove inadequate during tests, "stability bags" or "pericell" type finger segments can be added to the craft without changing the skirt/hull attachment points.

AUTOPILOT

Principle of Operation

Because the direction and magnitude of the thrust will be changing constantly to compensate for varying terrain and winds, complex and frequent commands will be necessary to keep the hovercraft on its intended course. Consequently, an on-board autopilot should be provided to accomplish assigned this task. Use of an autopilot frees the operator to concentrate on aiming and focusing the camera and on controlling forward speed, lift, and, perhaps, activation of gas or liquid sampling devices. Furthermore, by defining "forward" as the direction the TV camera is pointed, the operators work can be further simplified.

This type of vehicle control can be attained by mounting the camera and two velocity sensors* (one measuring craft speed parallel to the camera axis, the other measuring speed along the horizontal axis normal to the camera axis) on a stabilized platform that can be panned independently of the craft. The on-board autopilot would compare the desired forward speed (from the control console signal) with the actual forward and lateral speeds, in order to yaw the vehicle and apply thrust accordingly by commanding differential and collective pitch on the thrust rotors. As the craft is yawed, the camera and sensors would automatically pan in the opposite direction to maintain the proper camera heading. This closed-loop system would thus continuously drive the forward speed to the desired value and the lateral speed to zero. An additional loop, utilizing the output of a vertical accelerometer, will maintain a smooth hover. A block-diagram of the autopilot logic is shown in Figure 5 and a graphic representation of the operation is shown in Figure 6.

Control Console Configuration

The control console shown in Figure 7 has been designed so that a minimal amount of skill and training is required for the successful operation of the craft. The operator is faced with a single, primary control for camera (vehicle) direction and forward speed, and with secondary controls for lift power and for camera focus, tilt, and zoom. All camera controls are momentary actuators rather than proportional controls (to conserve electrical power and simplify operation), while the lift and velocity controls, which require somewhat finer adjustment, are proportional.

In operation, the operator selects lift power (there is a detent at the nominal value), aims the camera by momentarily turning the "T" handle clockwise or counter-clockwise, and selects his forward velocity by moving the "T" handle forward. To stop, he simply returns the velocity control to the "STOP" position and the on-board autopilot automatically applies the appropriate reverse thrust. The autopilot then maintains the vehicle's position by adjusting the direction and magnitude of thrust to cancel any

* These sensors would be either radar or ultrasonic Doppler shift sensors capable of measuring speeds of less than 1.0 fps.

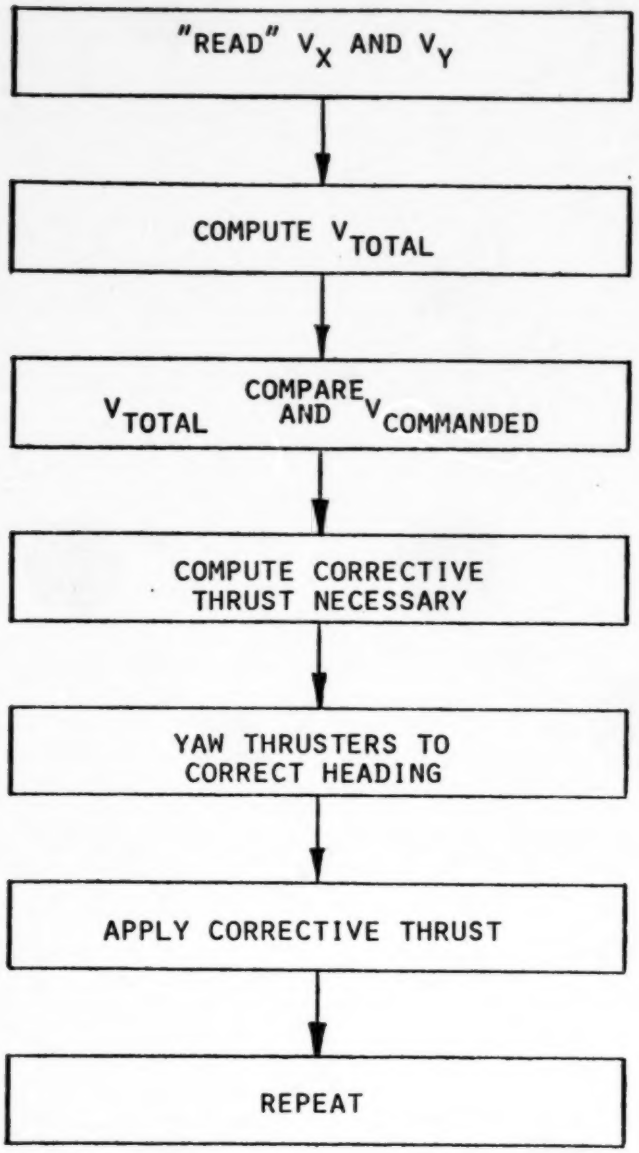
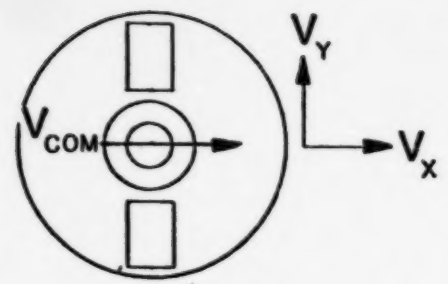
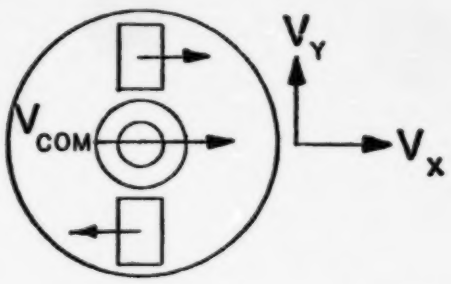


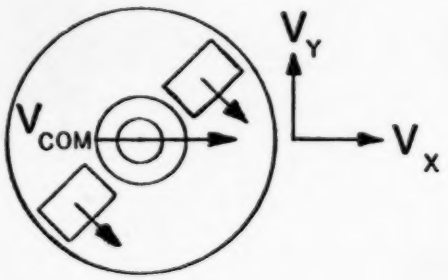
Figure 5. Autopilot logic.



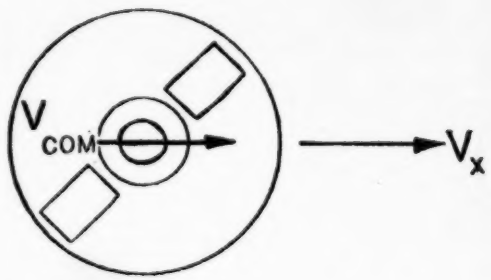
1. MEASURE/COMPUTE



2. YAW



3. THRUST



4. TARGET CONDITION

Figure 6. Illustration of autopilot operation.

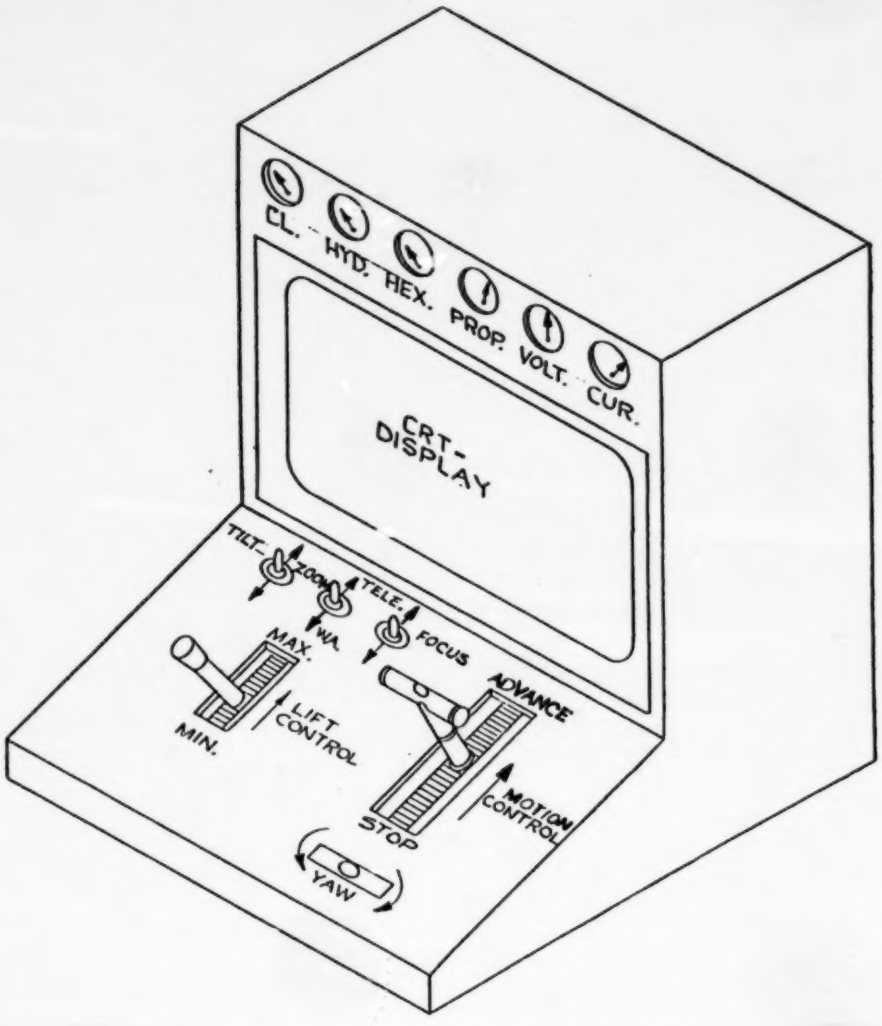


Figure 7. Prototype vehicle control console.

velocity in either the "x" (forward) or "y" (lateral) directions, until forward motion is again commanded. When an obstacle is encountered, the operator increases lift power until the obstacle is passed, then reduces lift to the nominal value to conserve battery power. The camera focus control is used to provide a sharp TV image. The tilt and zoom controls allow further tailoring of the scene presented on the monitor. These functions will automatically be driven to their nominal locations (0^{o} tilt and full wide-angle) by any command for forward motion. This will ensure that the operator sees the widest possible straight-ahead scene whenever the vehicle is in motion.

In addition to the vehicle and camera controls and the television monitor, the console will also include meters for the sensors on board, along with meters, warning lights, and buzzers to provide vehicle condition information (for instance, battery voltage, motor currents, and several local surface temperatures). A data recorder and a video recorder coupled with the console will provide a permanent record of the information presented for incident review and for training purposes.

On-Board Autopilot

The logic capability required for the autopilot is well within that of presently available microprocessor-based units. The autopilot will receive information from the two speed sensors (V_x and V_y), a vertical accelerometer, and the camera platform shaft (relative angle between camera heading and thruster direction). The information will be used to adjust the pitch of the two thrust rotors to yaw the vehicle (point the thrusters in the appropriate direction)* while simultaneously counter-rotating the camera platform and applying the appropriate forward thrust by the combined pitch of the two rotors. Minor adjustments to the lift fan output will also be made to cancel out any "bouncing" of the vehicle. This can all be done by a microprocessor much more quickly than by a human pilot, so that vehicle motion will be much smoother and better controlled. Figure 8 is a functional schematic of the autopilot.

ADDITIONAL ON-BOARD EQUIPMENT

In addition to the autopilot described in the preceding section, a number of other items carried on the vehicle will contribute to the satisfactory completion of the mission.

Stabilized Camera/Velocity Sensor Platform

For the video signal to be coherent, the camera must be stabilized in space. Motion along any of the three axes (x = forward, y = lateral, and z = vertical) does not present a significant problem as far as image quality is concerned, since these motions will be slow. But rotation about any of these axes (x, as list or roll; y, as tilt or pitch; and z, as pan

*Since the thrusters are bi-directional, it will never be necessary to yaw the vehicle more than 90^{o} to obtain the appropriate direction of thrust.

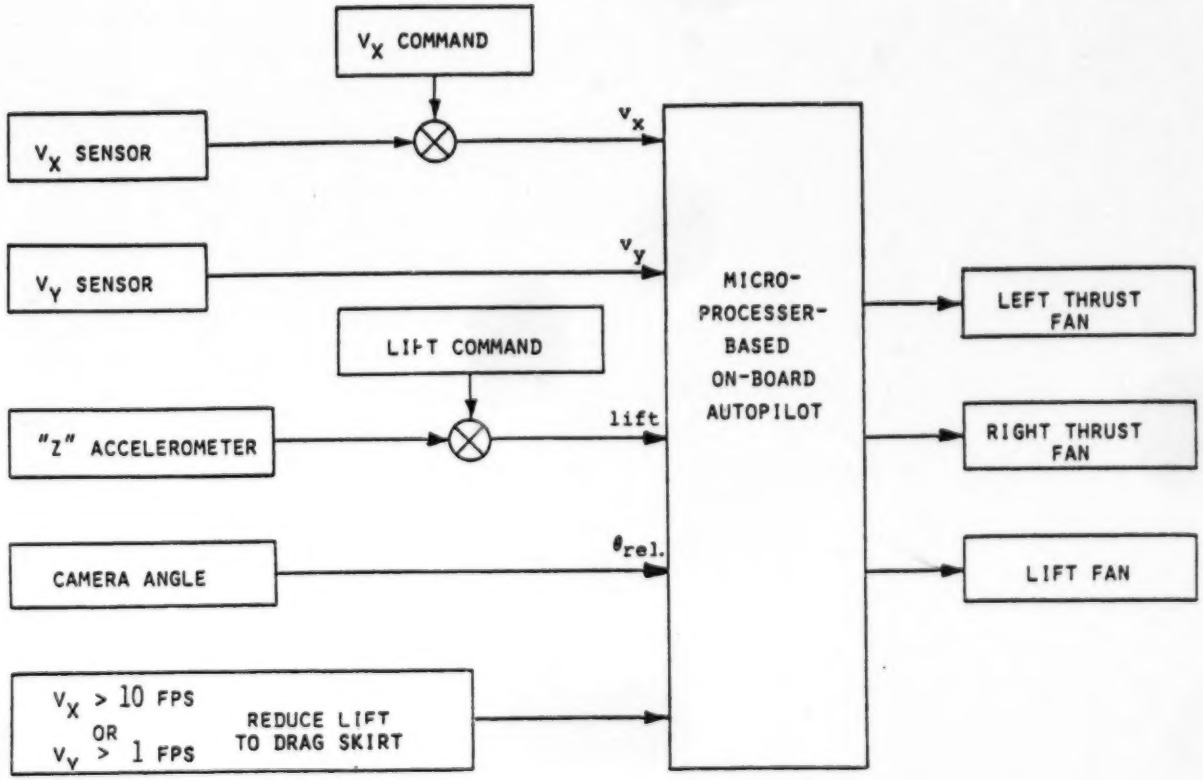


Figure 8. Prototype autopilot functional block diagram.

or yaw) creates a "slewing" of the video image that, when the rotation is fast enough or when rapid oscillations occur, results in an unrecognizable blur on the monitor screen. Pan angle information from the platform is fed to the autopilot to aid in the determination of the amount of vehicle yaw required for maneuvering, but except for this, the stabilized platform is independent of the autopilot. The stabilized platform's task is to use the information from platform-mounted inclinometers and/or rate gyros to drive servos that maintain a constant spatial orientation of the platform. Pan and tilt commands from the console will be inserted into the servo loops as artificial error signals, so that the null-seeking logic can provide both automatic stabilization and commanded deflections. The x-axis servo will be set to maintain a level attitude, the y-axis servo will be set to keep the camera axis parallel to the machine (unless tilt is commanded), and the z-azis servo will be set to maintain the camera heading called for by the operator. For the velocity sensors to function properly, they must be mounted with the camera on the stabilized platform. In this manner, the x- and y-axes remain relative to camera heading.

Data-gathering Equipment

As previously mentioned, a number of options exist for on-board data-gathering equipment. Among these are a wide range of individual gas sensors, simple detectors, or samplers. Each vehicle should be tailored to its user's requirements by the installation of specific sensors (and, perhaps, having the option of "plugging in" substitute units). Work sponsored by NASA is currently in progress on a compact, lightweight mass spectrometer that may be suitable for use on the vehicle. A microphone and speaker could provide communications with any personnel in the spill area.

Vehicle "Housekeeping" Equipment

The vehicle must have all the equipment necessary to respond to commands from the operator and/or autopilot (servo-motors, actuators, etc.) The vehicle must also carry sensors to provide the operator with information about the condition of the vehicle itself, as well as the environment in which it is operating. Examples of the data that such sensors could transmit to the console are battery voltage, motor currents, and an array of vehicle surface temperatures.

WEIGHT BREAKDOWN/POWER REQUIREMENTS

The determination of vehicle weight and of the power necessary to operate satisfactorily is an iterative process--as the weight increases, the power requirements increase and, hence, total battery and motor weight increases. The values presented in Tables 2 and 3 result from such an iteration and are based on the performance and equipment requirements set forth in the preceding sections.

TABLE 2. ANTICIPATED POWER REQUIREMENTS

Item	Power (watts)
Lift fan motor (5 hp)	4500*
Thrust fan motors (2 @ 5 hp)	9000*
RF receiver and autopilot logic	5
Servos for camera platform and rotor pitch control	400
TV camera	30
Spotlights	200
Audio (speaker/microphone)	10
Data-gathering equipment (sensors/samplers)	200**
RF transmitter (video and data)	5***
Miscellaneous (vehicle condition sensors, other power needs)	50
TOTAL	14400

*Based on 746 watts/HP and 83% motor efficiency, which yields 900 watts/HP. These are maximum values.

**Based on 4 typical sensors and 2 samplers.

***Typically, 1 to 2 watts would suffice; a 5 watt transmitter will be used to assure adequate signal strength.

TABLE 3. ANTICIPATED WEIGHTS

Item	Weight (lb)
Structure	70
Batteries (14400 watts @ 300 watts/lb)	48
Lift motor	6
Lift fan	11
Thrust motors	12
Thrust rotors (incl. pitch mechanisms)	24
Skirt cushion and bag	40
Stabilized platform (incl. camera, velocity sensors and servos)	28
Receiver/transmitter	6
Autopilot	6
Gas sensors/samplers	20
Miscellaneous	15
TOTAL	286

VEHICLE PERFORMANCE

Table 4 summarizes the performance characteristics anticipated for the vehicle, based on the weights and powers set forth above. Endurance is difficult to estimate, since it depends so strongly on the demands placed on vehicle performance by the particular mission. Based on the battery characteristics (300 watts per pound, 450 watt-hours per pound), total endurance on the order of 1.5 hours can be expected with all functions operating at maximum power. However, one can reasonably expect that both lift and thrust will be called for at average levels substantially below the maximum (perhaps, 50% for lift and 30% for thrust). Since these two functions combined draw over 93% of the peak power requirement, total endurance could reasonably be increased almost two and one-half times, i.e., to over 3.5 hours. Assuming an average mission time of 20 to 30 minutes, the system has the capacity for between 7 and 10 missions before the batteries must be replaced.

TABLE 4. PROTOTYPE VEHICLE PERFORMANCE CHARACTERISTICS

Characteristic	Expected Performance
Maximum speed	10 fps
Maximum grade capability	20 degrees
Maximum crosswind	25 knots
Maximum obstacle height	18 in.
Range (from command post)	0.5 mile
Endurance (with new batteries at maximum power consumption)	1.5 hr
Turning circle diameter	0 in.*

* The vehicle can rotate, in place, about its own axis.

COST ANALYSIS

Since the development of this vehicle is largely dependent on advances in sub-system technologies (such as battery and DC-motor developments), the determination of vehicle costs must be, to a certain degree, speculative. This section will present current best estimates for the engineering costs and anticipated equipment costs.

Prototype System Development/Testing Costs

The preliminary cost estimates for detail design, fabrication, testing, demonstration, and follow-up servicing of the prototype vehicle (including vehicle sensors, control console, and video and data recorders) can be broken down as shown in Tables 5 and 6.

TABLE 5. PROTOTYPE LABOR COSTS

Source of Cost	Estimated Cost ($)
Design Costs:	
Structure and mechanicals	35,000
Electronics	30,000
Fabrication Costs:	
Structure and mechanicals	50,000
Electronics	40,000
Testing Costs:	
Electronics	10,000
Total craft	30,000
Demonstration/follow-up servicing	10,000
Total Labor Costs	205,000

TABLE 6. PROTOTYPE MATERIAL COSTS

Item	Estimated Cost ($)
Structural and mechanical materials	20,000
Skirt system	5,000
TV camera w/zoom lens	4,000
Velocity sensors (2)	4,000
Gas sensors (2)*	4,000
Accelerometer, inclinometers, and servomotors	7,000
Motors (35 HP DC brushless)	30,000
Lift fan and thrust rotors	6,000
Battery pack**	15,000
Electronic materials (for fabrication of receivers, transmitters, console, and autopilot	15,000
Video recorder	2,000
Data recorder	5,000
Total Material Costs	$ 117,000
Total Prototype Cost	$ 322,000

*The remaining complement of sensors could be selected and purchased by the agency chosen to field-test the prototype.

**Substantial savings could be realized by substituting lower energy-density, rechargeable batteries on the prototype and accepting the reduced performance and endurance.

Pre-Production Vehicle System Costs

Because many of the costs (in both labor and materials) involved in development of the first prototype vehicle system are non-recurring, the cost of pre-production units should be considerably lower. The following costs are based on a pre-production run of 10 systems--the unit cost for fewer than 10 systems would be higher, while the cost for true production quantities would be substantially reduced.

Operating Costs

Operating costs can be broken down into two categories: scheduled maintenance and mission costs.

A vehicle of this complexity (and importance) should receive a thorough check-out at least monthly. This should require only one-half to one day for a qualified technician, at a cost to the operator of only $150 to $200 per month.

The cost per mission is more difficult to define since a number of variables enter into the computation The only expendable item on the craft is the battery pack. If one assumes (conservatively) 6 missions per pack, then the cost per mission for batteries is $500. In addition, perhaps $100 is required for video and data tapes. These are the only two predictable costs. In the event that the vehicle sustains any damage, the cost of repair could range from a few hundred dollars to very nearly the cost of a new vehicle. Over a normal, "non-catastrophic" lifetime, the vehicle can be expected to perform anywhere between 50 and 100 missions, representing a mission cost of between about $2,000 and $3,500 (including battery and recording materials costs).

Cost/Benefit Analysis

Lest the purchase and operating costs of the vehicle be perceived as too high to justify its existence, one should consider the cost of the "machine" the hovercraft is designed to replace, namely, a man. Although the "cost" of a man far exceeds the amount of money spent on training, salary, and, perhaps, disability or death benefits, these numbers alone are sufficient to demonstrate the value to society of removing personnel from a hazardous situation. A study by the Stanford Research Institute on the cost effectiveness of various marine fire-fighting alternatives used the following average costs: $30,000 per injury (involving 3 days or more disability) and $300,000 per death. By other standards, these values are quite conservative.

Since the degree of damage sustained by the craft would most likely correspond to the degree of injury to a man in the same situation, it can be seen from the anticipated cost data that the vehicle is economically the proper choice for those instances involving high risk. And, in instances of relatively low risk, the mission cost of the vehicle is so low that it represents, in essence, inexpensive insurance.

TABLE 7. PRE-PRODUCTION VEHICLE COSTS

Labor Costs Item		Estimated Cost ($)
Re-design based on prototype user's inputs (amortized over 10 vehicles)		3,000
Fabrication		45,000
Testing/check-out		6,000
Material Cost Item		
Structural and mechanical materials	$	12,000
Skirt system		3,000
TV camera w/zoom lens		3,000
Velocity sensors (2)		3,000
Gas sensors (6)*		10,000
Accelerometer, inclinometers, and servo motors		6,000
Motors (35 H.P. DC brushless)		18,000
Lift fan and thrust rotors		6,000
Battery pack		3,000
Electronic materials		12,000
Video recorder		2,000
Data recorder		5,000
Cost Summary		
Total Labor Costs/Vehicle	$	54,000
Total Material Cost/Vehicle	$	81,000
Total System Cost/Vehicle	$	135,000

*Selected by the final customer - 4 installed 2 substitute.

Furthermore, there is an excellent chance that total property damage from a spill incident would be reduced if the vehicle were used, because it allows the site commander to develop his strategy more quickly and based on more complete information. The faster response made possible by remote reconnaissance would, in addition, reduce the amount of spilled chemicals introduced into the environment.

The vehicle provides yet another benefit--a permanent record (video tape and charts) of what happened--which can be an invaluable training aid.

Even if one were to ignore the economic considerations of the issue, the vehicle offers a reduction in threat to human life and should be considered for this reason alone.